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Ligno-cellulosic biomass exploitation for power generation: A case study in sicily

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ABSTRACT

During the most recent years, among the different forms of renewable energy sources, biomass is playing an important role in the strategic agenda of European Community. Many countries, including Italy, have introduced important incentive schemes to support the use of biomass for electricity, heat and transportation. This has raised considerable interest towards the use of biomass for energy production. Nonetheless, the investment on biomass fuelled power plants presents several critical issues, such as choice of feedstock composition, economic viability with regard to plant size, access to locally available biomass and price of feedstock. This case study attempts at an evaluation of the economies originated by a small scale (<1 MW_{el}) Organic Rankine Cycle (ORC) turbine coupled with a biomass fuelled boiler, fed by residual biomass from local cultivations, located in a rural area of a typical Mediterranean semi-arid environment in inland Sicily. A Geographical Information System (GIS) was used as a tool to assess the power plant economic viability with respect to local biomass availability and localization. Plant financial viability was evaluated for a number of different scenarios based on power plant size, number of yearly operational hours, feedstock mix and price.

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1. Introduction

Renewable energy sources (RES) play a key role in the current European Union (EU) strategies to mitigate the impact of global warming. Among the different forms of renewable sources, biomass is undoubtedly one of the most promising.

In particular, the use of agro-residues may contribute to the share of renewable energy sources, hence to the decreasing of fossil fuel imports [1,2]. Furthermore, the use of agro-residues leads to important environmental benefits, such as the reduction of atmospheric CO_2 concentrations and its greenhouse effect [3]. Therefore, biomass, among renewable energy sources, plays a key role in the political agenda in most of the EU member states [4].

Biomass is used to meet a variety of energy needs, including electricity, transport, household and industrial heating. Various studies forecast an increase in its contribution to the future energy supply, both at a regional and a global level [5–7].

In year 2005 the European Commission "*Biomass Action Plan*" [8] set a target for increasing use of biomass from about 289,000 TJ in 2003 to about 628,000 TJ in 2010, due to many advantages of biomass over conventional fossil energy sources, such as "lower costs, less dependence on short-term weather changes, promotion of regional economic structures and provision of alternative sources of income for farmers".

By June 2010 all the Europe Member States were required to submit national renewable energy action plans (NREAPs). According to the NREAPs, in year 2010, biomass delivered more than 83 Mtoe to the EU's energy consumption: 12% in electricity, 18% as transportation fuels and 70% as heat [9]. Heating will continue to being by far the most important sector for bioenergy in 2020. Taking into account that heat covers more than half of the final energy consumption in Europe, biomass should be a key sector for EU Members to meet the 2020 targets. By 2020, biomass supply in Europe should increase to meet the demand of all sectors of heat, electricity and transport biofuels, rising from 77 Mtoe in 2006 to 122 Mtoe in 2020. Even though the main focus of the paper is on the technical and economic viability of lingo-cellulosic biomass (coming from agro residues) exploitation for power generation, for the sake of completeness it is important to remark that the debate about biofuels has still several controversial elements related to the correct accounting of their environmental implications [10]. In particular, in the studies taking into account energy uses of biomass in a life cycle perspective, very different conclusions can be drawn according to some important issues, such as: accounting of biogenic carbon, boundaries of the studied system, functional unit definition, treatment of the by-products of the investigated feedstock

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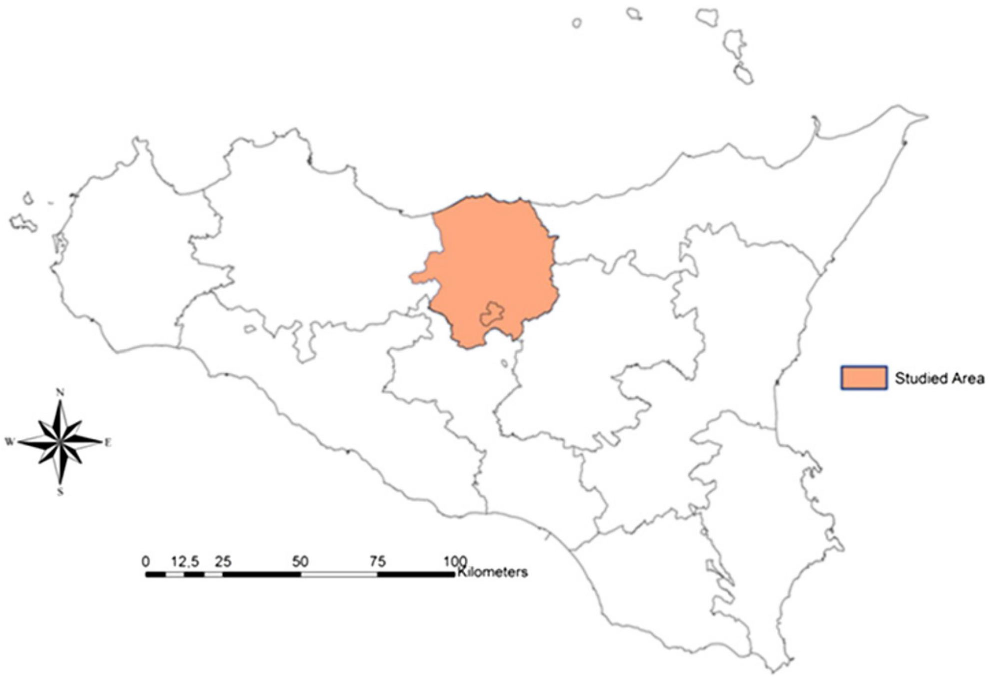

Fig. 1. Localization of the studied area.

[11–13]. Additionally, even though many life cycle assessment (LCA) studies on biofuels in general indicate greenhouse gases (GHG) benefits, they have severe drawbacks in the area of toxicity and eutrophication [12], since they overlook the creation of pollutants other than carbon dioxide [14]. A careful investigation of the above mentioned aspects should be carried out in order to rationally use studies to support biofuel policy making.

Forests and forest based industries are key contributors to biomass supply [15,16], and this should still be the case in 2020, however the biggest increase should come from agriculture [9]. The agro-food sector is particularly important and could have the potential to offset substantial amounts of GHG emission compared to other fuel sources as energy source [17]. Concerning Sicily, especially in some agricultural areas of the region, fostering the agro-food

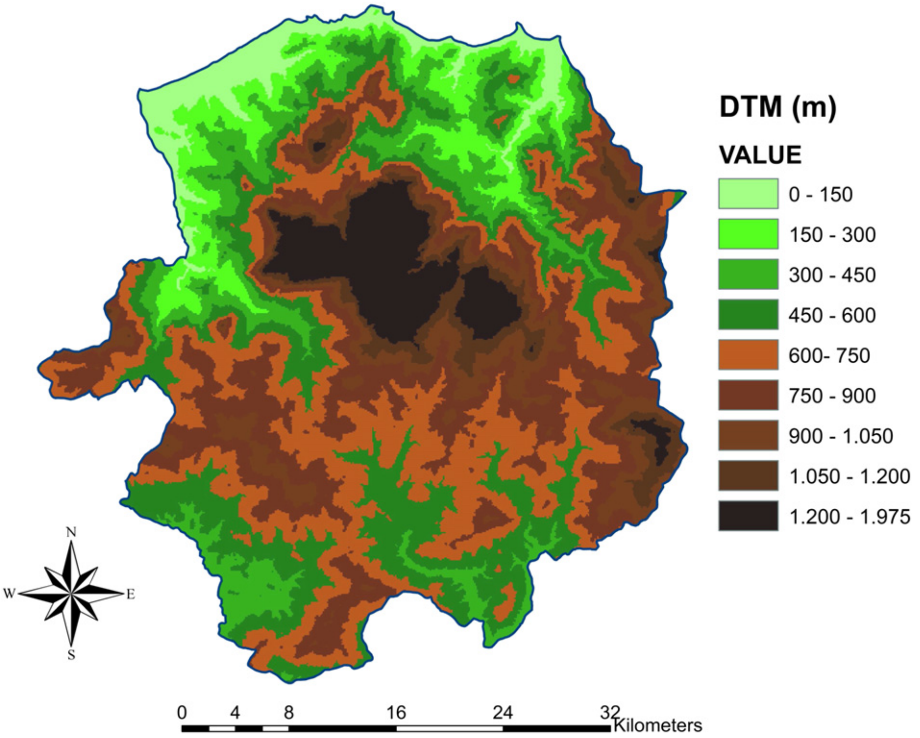

Fig. 2. Digital Terrain Model (DTM) of the studied area.

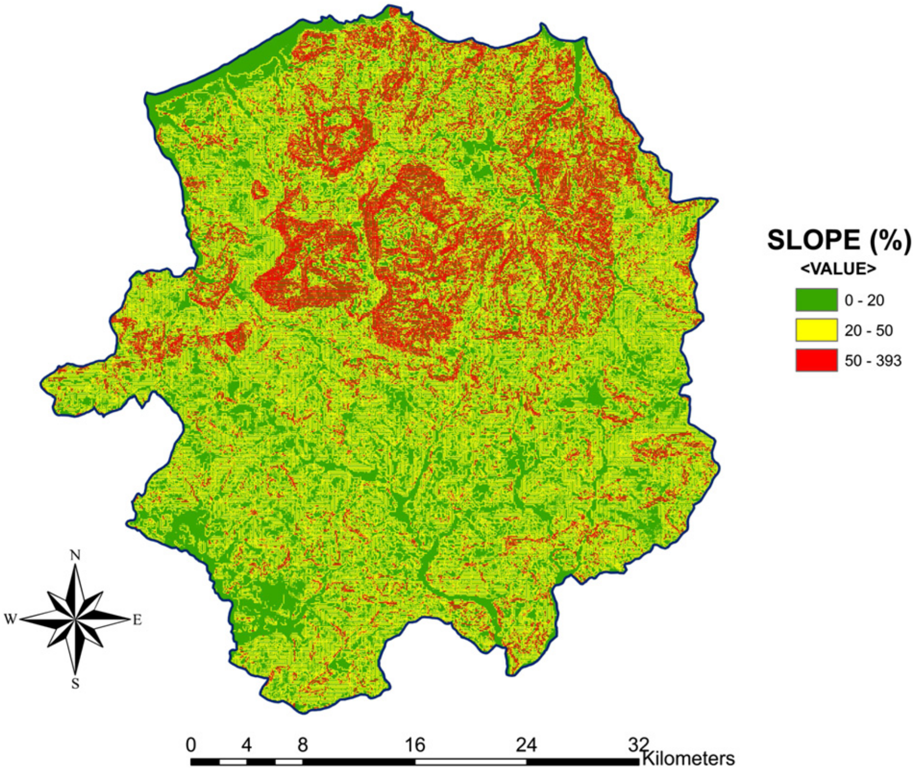

Fig. 3. Slope map of the studied area.

sector could significantly contribute to the local agricultural development [18] and the development of parallel resources (such as power generation from agro-waste), in line with current European agricultural policies and regional energy master-plan [19].

Moreover, the integration of biomass in regional energy planning may benefit of existing advanced tools that allow thorough cost assessments aimed at identifying feasible location for biomass-based investments [15,20,21].

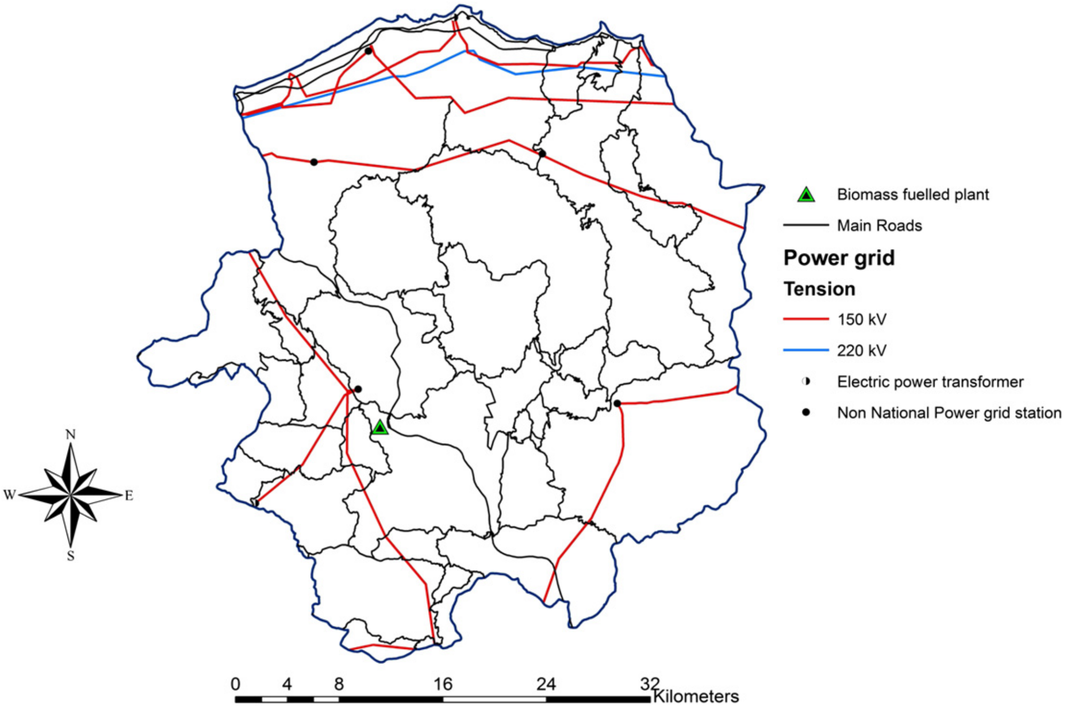

Fig. 4. Map showing the main roads and power grid networks within the studied area.

Table 1
Amounts of feedstock obtainable for the different distances from the plant.

Distance from plant location (km)	Non-irrigated arable land area (ha)	Olive groves area (ha)	Wheat straw[a] (t)	Chipped wood[b] (t)
7	12,034.83	85.33	36,104.48	213.34
10	19,868.57	1532.09	59,605.70	3830.21
15	32,784.54	3481.68	98,353.61	8704.20
20	42,483.80	4366.29	127,451.39	10,915.73

[a] 15% moisture content.
[b] 30% moisture content.

Table 2
Main plant parameters.

Boiler and ORC turbine	Values
Power plant size [kW]	600 kW_{el} ÷ 1000 kW_{el}
Running hours per year	6000 h ÷ 8000 h
Boiler and heat exchange efficiency	0.85
ORC cogenerator power efficiency	0.21
Losses	0.02

The rather jeopardized geographical distribution of biomass has increased the interest for the utilization of Geographical Information Systems (GIS) as a tool for the evaluation of feedstock supply, estimation of transportation costs and choice of power plant siting.

Numerous researchers have used GIS to map the availability of renewable energy resources in several regions of the world [22–26]. Noon and Daly [27] proposed a GIS-based decision support system to assist the Tennessee Valley Authority in estimating costs for supplying wood fuel to its 12 coal fired power plants. The authors were able to efficiently analyse the transportation networks and estimate distances and costs. Voivontas et al. [28] developed a GIS-based decision support system (DSS) to estimate the potential of power production from agriculture residues in Creta (Greece) and implemented a method providing tools to identify the geographical distribution of biomass with a close eye on the whole economics of feedstock supply. Vasco and Costa [29] published a GIS-based study aimed at the use of forest biomass residues in Maputo province (Mozambique).

Panichelli and Gnansounou [21] developed a GIS-based decision support system for selecting least-cost bioenergy chain locations in cases of significant variability in biomass price at the farm gates and in different provinces. The analysis was used to find the optimal locations for biomass based torrefaction and gasification units.

Freppaz et al. presented a GIS-based DSS for forest biomass exploitation at regional level [30]. In that study, GIS was integrated to mathematical methods, to investigate biomass use for both thermal and electric energy production in the area under analysis.

As discussed above, the use of GIS to locate and size biomass-fuelled energy facilities has already been explored in literature. In addition to previous works, this article offers specific methodology to assess financials of a local biomass energy chain under the specific conditions of the Mediterranean arid landscape.

The present study uses GIS as a tool to evaluate the energy potential of agricultural by-products such as wheat straw and tree pruning and trimmings collected in a 1583.10 km^2 rural area of inland Sicily (Italy) (Fig. 1) to feed an Organic Rankine Cycle (ORC) turbine coupled with a biomass fuelled boiler.

The plant size was chosen with regard to the actual Italian incentive schemes for biomass energy production. The current Italian biomass power plants incentive scheme [31] defines two different types of plants (small size, i.e. <1 $MW_{el,}$ and large size, i.e. >1 MW_{el}) and two different types of incentives based on electrical energy selling price (fixed or market based).

Small plants fuelled with biomass collected within a 70 km radius from the plant location may dispatch the net energy at a fixed flat rate price of 280 € MWh_{el}^{-1} for a 15 years period. Large

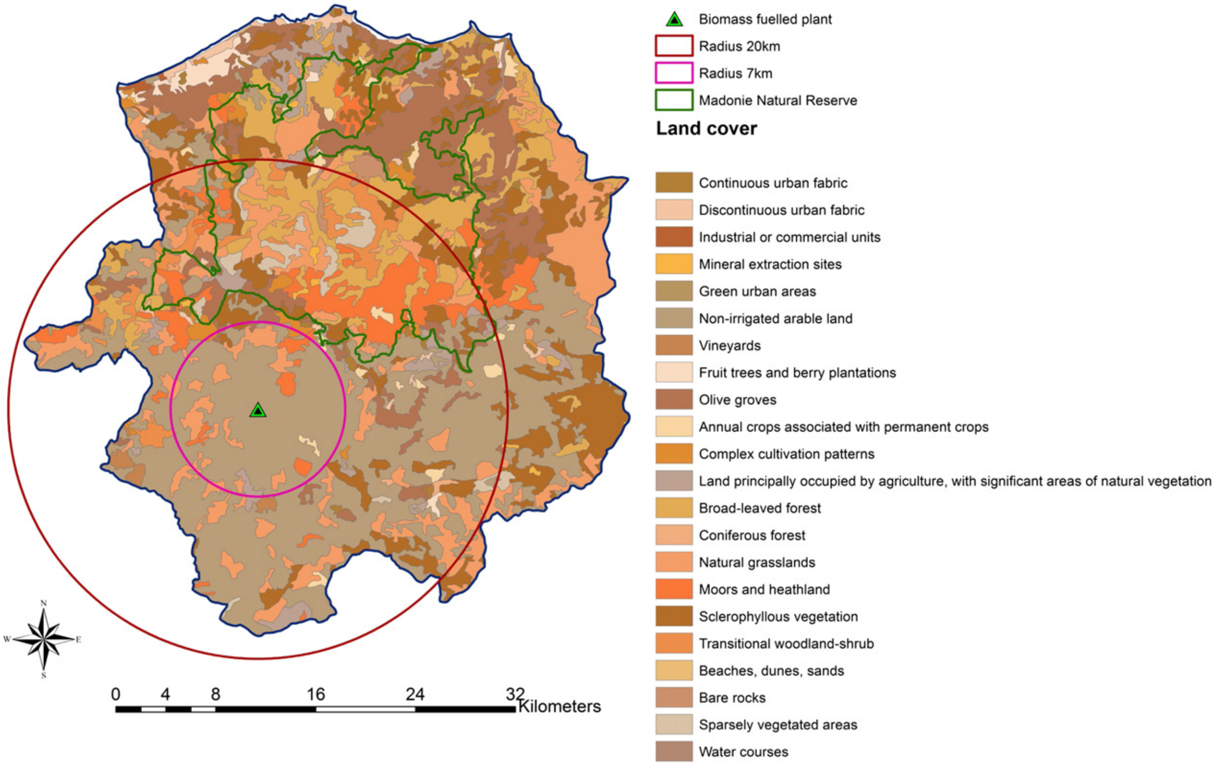
Biomass fuelled plant
Radius 20km
Radius 7km
Madonie Natural Reserve
Land cover
Continuous urban fabric
Discontinuous urban fabric
Industrial or commercial units
Mineral extraction sites
Green urban areas
Non-irrigated arable land
Vineyards
Fruit trees and berry plantations
Olive groves
Annual crops associated with permanent crops
Complex cultivation patterns
Land principally occupied by agriculture, with significant areas of natural vegetation
Broad-leaved forest
Coniferous forest
Natural grasslands
Moors and heathland
Sclerophyllous vegetation
Transitional woodland-shrub
Beaches, dunes, sands
Bare rocks
Sparsely vegetated areas
Water courses
N
W
E
S
0
4
8
16
24
32
Kilometers

Fig. 5. Land use map of the studied area.

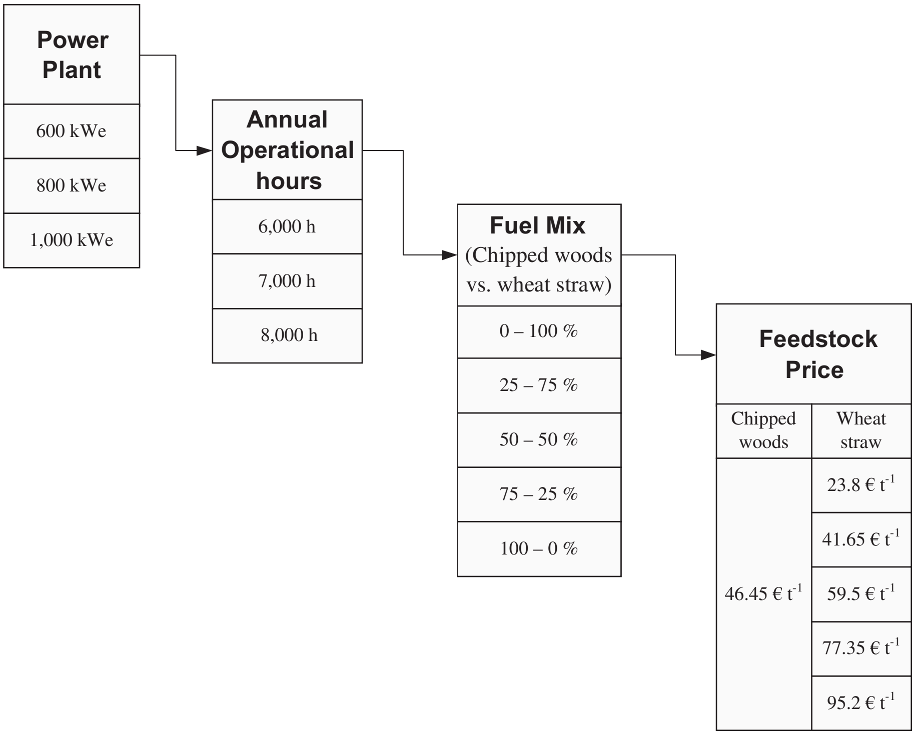

Fig. 6. Schematics of the scenario analysis.

power plants may only dispatch the net electricity at current market price and gain No.1 Green Certificate (GC) per each MWh$_{el}$ produced. Hence, large plants are affected by a higher uncertainty related to the price variability of green certificates. Moreover, the regional energy master plan [19] poses significant limitations to installation of large power plants. Thus the analyses carried out in this paper are focused on three small size power plants: 600 kW$_{el}$, 800 kW$_{el}$ and 1000 kW$_{el}$.

Table 3
Data for evaluation of plant economics.

Data	Values
Price of chipped wood[a]	46.45 € t^{-1}
Price of straw[b]	23.8 € ÷ 95.2 € t^{-1}
Specific transportation costs [51]	5.8 × (avg transportation distance [km])$^{-0,6}$
Average transportation distance from selected site for chipped wood[c]	0 ÷ 20 km
Average transportation distance from selected site for straw[c]	0 ÷ 7 km
Cost for ashes disposal [2]	80 € odt^{-1}
Chipped wood ashes content [49]	3% odt t^{-1}
Straw ashes content [49]	10% odt t^{-1}
Cost for boiler and biomass feeder	440,000 € MW$_{th}^{-1}$
Cost for ORC module	1,392,000 € MW$_{el}^{-1}$
Costs for design and site supervision[d]	10% of installation costs
Debt and equity over investment [%][e]	80% debt 20% equity
Feed in tariff [31]	280 € MWhr^{-1}
Cost of electrical energy[f]	120 € MWhr^{-1}
Operational and maintenance cost [51]	4%

[a] Average value from [21,49], 30% humidity content.
[b] Average value from [49], 15% humidity content.
[c] Calculated from GIS see Figs. 4 and 5.
[d] According to current prices determined by the local institution of civil and mechanical engineers and available at the website http://www.ingpa.it.
[e] According to local credit market conditions.
[f] Current average market price for electricity to industry consumer as reported at the website http://www.mercatoelettrico.org.

2. Materials and methods

A GIS was used to assess the quantity and the local distribution of feedstock. The themes used within the system include: land use, road infrastructures and power grid, digital terrain model (DTM) (Fig. 2) and slope map (Fig. 3). The application was implemented by means of the freely available software gvSIG (version 1.1), in order to take advantage of a number of spatial analysis tools.

A series of spatial queries allowed the identification of the areas suitable for biomass supply (wheat cultivations and olive groves) as well as the main roads network. The amount of available biomass was obtained for different distances from the supposed plant location (namely 7, 10, 15 and 20 km).

The DTM was created with a sampling interval of 30 m. The total amount of feedstock available was calculated knowing the specific amount of residual biomass obtainable by each class of cultivated land.

The collected data allowed an economic analysis, which supports the investment decision making process. The analysis takes into account investment costs, running and financial costs as well as plant revenues based on applicable feed in tariff in accordance to current Italian national incentive scheme [31].

A calculation spreadsheet was used to compute results and simulate a number of different scenarios based on power plant size,

Table 4
Data for evaluation of plant financials.

Data	Values
Bank annual interest rate	6%
Loan amortization (years)	10
Weighted average cost of capital (WAAC)	8%
IRR threshold value[a]	15%

[a] Value for medium risk averse investor according to current financial market conditions.

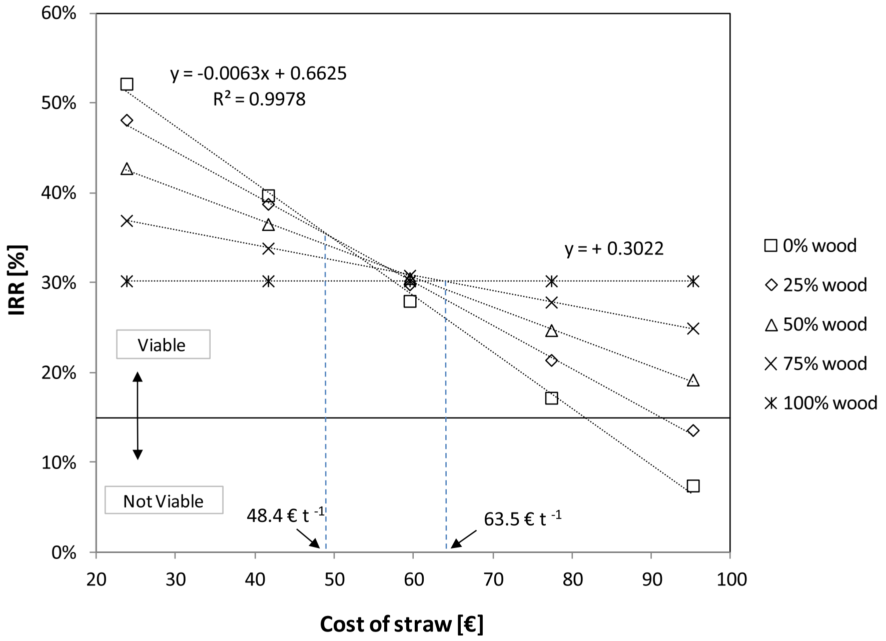

Fig. 7. IRR [%] with respect to cost of straw for different fuel mixes (1000 kW_{el} plant size; 6000 operational hours).

number of operational hours, fuel mix and price of feedstock. Plants of three different sizes (600 kW_{el}, 800 kW_{el} and 1000 kW_{el}) are assumed to work for 6,000, 7000 and 8000 annual operational hours with different fuel mix based on the percentage of chipped wood vs. wheat straw. The financial viability of each scenario is then calculated with respect to feedstock price.

The primary energy need of the plant is calculated per each scenario based on plant thermal and electrical efficiency. The value, coupled with feedstock lower heating values (LHVs) is then used to compute the amount of feedstock needed. The amount of energy produced, per each of the assumed scenarios, deducted by the electrical self-consumption of the plant and multiplied by the flat rate feed in tariff, allows computation of plant gross revenue.

The financial evaluation of the initiative was based on the Discounted Cashflow method (DCF). 15 years of future cashflows generated by the investment are discounted at present date through a discount rate calculated as the Weighted Average Cost of Capital (WACC).

The scenario analysis allowed calculation of the following financial indicators [32]:

- *average annual revenue*, calculated as the arithmetic average of 15 years annual revenues;
- *average annual free cashflow*, calculated as the arithmetic average of the 15 years annual free cashflows;
- *net present value (NPV)*, calculated as net value of all future cashflows discounted at present date by WACC;

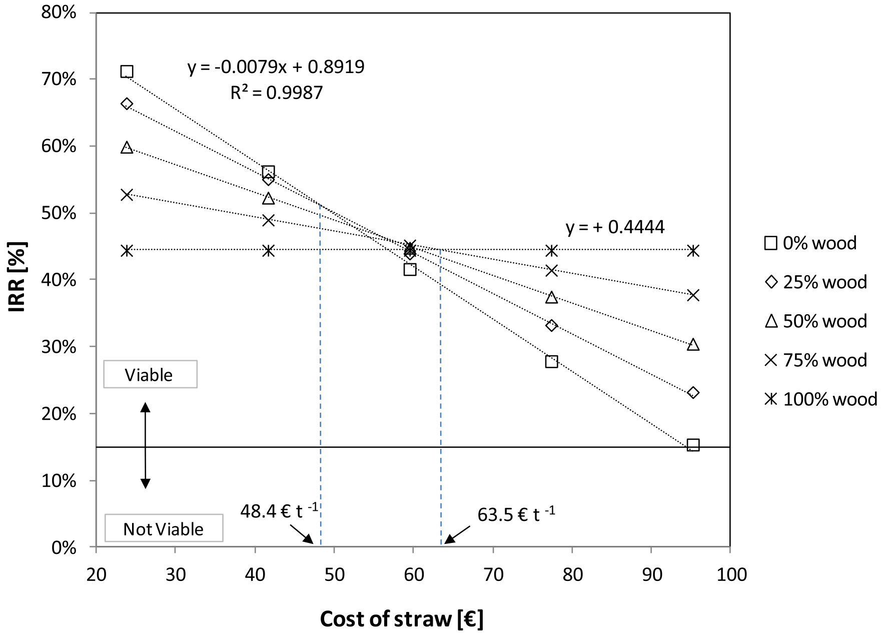

Fig. 8. IRR [%] with respect to cost of straw for different fuel mixes (1000 kW_{el} plant size; 7000 operational hours).

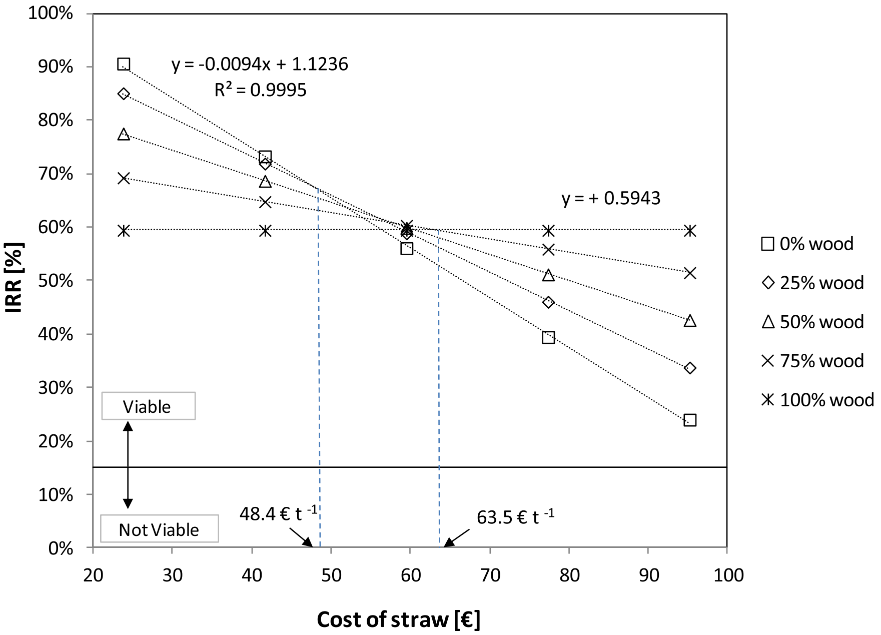

Fig. 9. IRR [%] with respect to cost of straw for different fuel mixes (1000 kW$_{el}$ plant size; 8000 operational hours).

- *return on sales (ROS)*, calculated as average annual free cashflows over average annual revenues;
- *return on investment (ROI)*, calculated as average annual free cashflows over total investment;
- *return on equity*, calculated as average annual free cashflows over equity;
- *benefit cost ratio (BCR)*, calculated as NPV over total investment;
- *compound equity payback time (EPbT)*, calculated as the number of years necessary to payback the investment with future cashflows discounted by WACC;
- *internal rate of return (IRR)*, calculated as the discount rate at which the net present value of negative cashflows of the investment equals the net present value of the positive cashflows.

The IRR was taken as the ultimate value for determining financial viability of each of the scenarios under analysis.

3. Description of the case study

Inland Sicily is mostly a typical semi-arid Mediterranean environment strongly voted to agriculture, in particular wheat and olive cultivation. The area under analysis shows significant availability of wheat straw and olive tree pruning, however the road infrastructure is remarkably undeveloped and the land property highly patchy: the average property size is less than 2 ha [33].

The studied area is located within Palermo province (northwest Sicily, see Fig. 1) and is covered by some 512.63 km^2 of non-irrigated arable land, 6.06 km^2 of vineyards, 179.95 km^2 of olive groves,

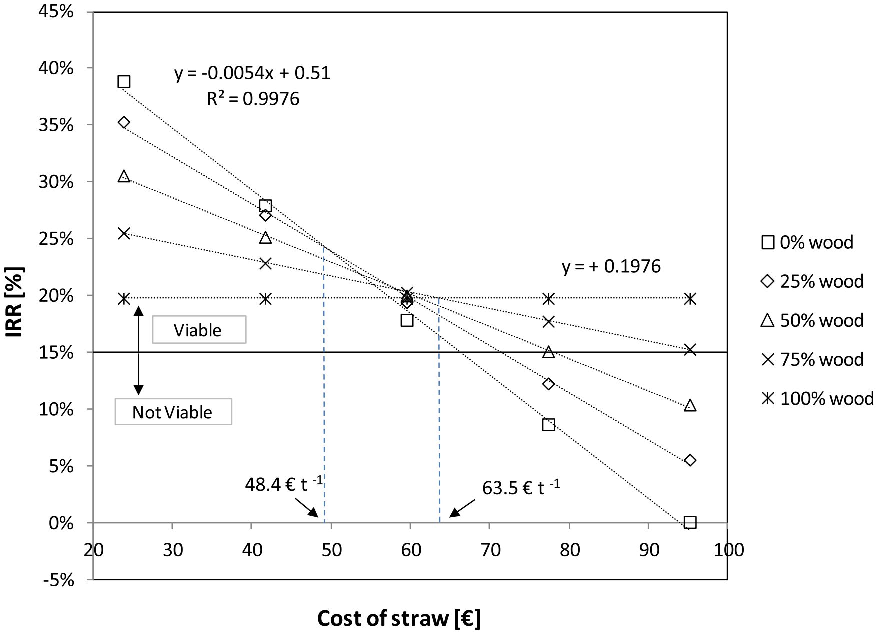

Fig. 10. IRR [%] with respect to cost of straw for different fuel mixes (600 kW$_{el}$ plant size; 6000 operational hours).

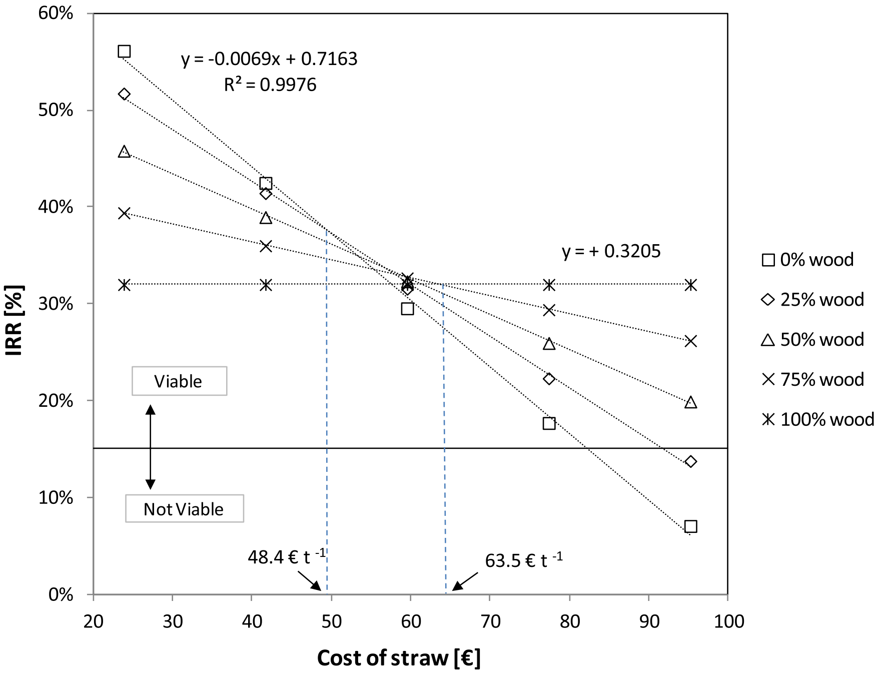

Fig. 11. IRR [%] with respect to cost of straw for different fuel mixes (600 kW_{el} plant size; 7000 operational hours).

14.69 km^2 of fruit cultures and 503.71 km^2 of heterogeneous arable land.

The land composition shows potential for residual feedstock available for power generation. In particular the feedstock could be composed by wheat straw and chipped wood obtained from trimmings and pruning of olive trees. The plant location was chosen considering distance from existing national power grid, road network access, existing land use and terrain slope (<50% in the vast majority of the land supplying feedstock to the plant; see Fig. 3). Fig. 4 shows the assumed plant location as well as the main roads and the national power grid infrastructures. The amounts of feedstock obtainable (reported in Table 1) are calculated considering that some 3 t ha^{-1} of wheat straw are produced yearly through wheat and cultivation [34,35] and 2.5 t ha^{-1} of chipped wood are produced yearly through olive trimmings and prunings [36]. This latter datum is in line with the one used in [37] and quite realistic, on the average, for all the Mediterranean area.

Fig. 5 shows the land use map of the studied area and two circles centred in the chosen plant location and respectively with 7 km and 20 km radius, which correspond to the minimum and maximum distances explored in this case study.

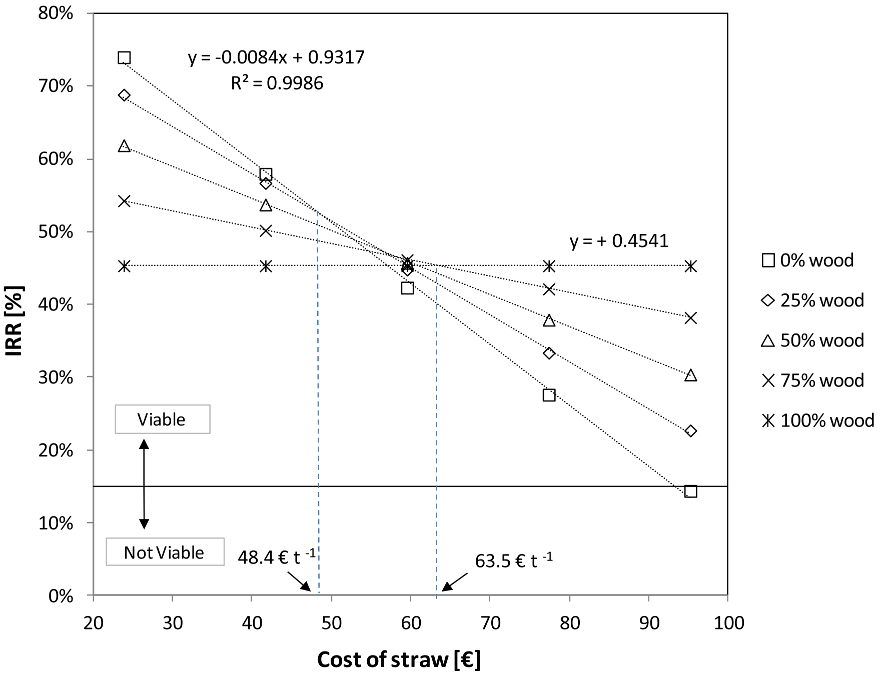

Fig. 12. IRR [%] with respect to cost of straw for different fuel mixes (600 kW_{el} plant size; 8000 operational hours).

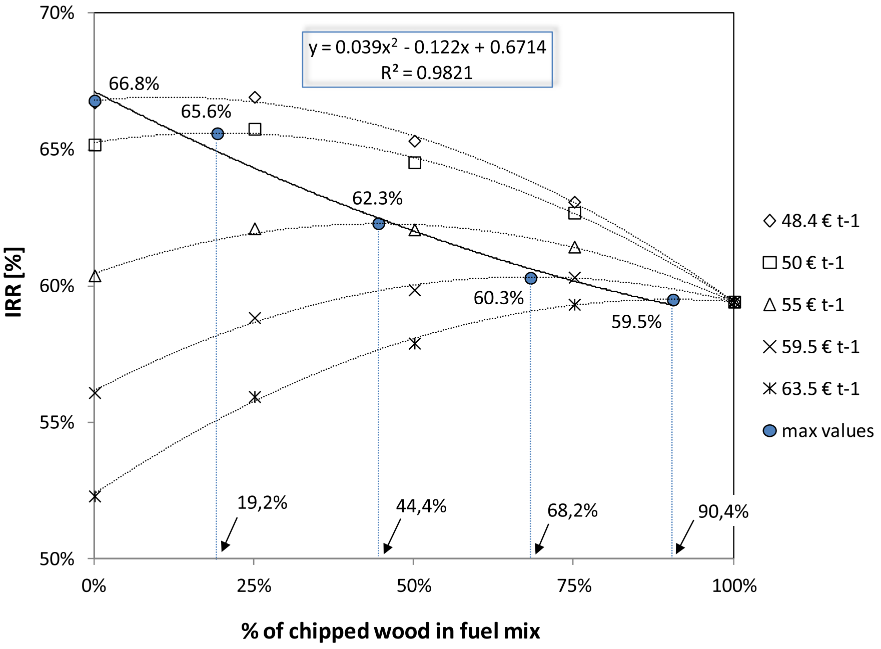

Fig. 13. IRR [%] with respect to feedstock composition for different wheat straw prices. The black bold curve fits the maxima IRRs obtained for each wheat straw price; its equation is showed in the upper part of the figure.

Farmers generally bear substantial costs to dispose of this residue, as a consequence, the use of residual feedstock for energy production may represent an opportunity to create new economies which may foster the local agricultural sector as a whole and cause no substitution of food crops with energy crops.

Energy conversion of straw and wood residuals could be based on an Organic Rankine Cycle (ORC) generator coupled with a diathermic oil boiler (up to 300 °C temperature [38]) or a gasification unit coupled with an alternative engine. ORC is a consolidated technology for biomass-based energy production and, if compared to steam turbines, shows some significant advantages such as lower maintenance costs and easier plant management [39–45].

Gasification is undoubtedly a promising technology, due to higher efficiency of alternative engines compared to ORC turbines. However, it could be critical with respect to maintenance and management. Most of the problems arise because of the syngas cooling and cleaning process [46,47]. These criticalities may cause longer maintenance times and lower energy production. On the other hand, modern boilers boast high efficiencies and reliability [48], hence, a boiler coupled to an ORC system, seems the most suitable choice for a practical application such as the one developed in this paper. In economical terms, albeit gasification might induce lower costs and higher profits, the above mentioned criticalities seem still too high to sustain sufficient investment risk mitigation.

In ORC systems the boiler is coupled with a heat exchanger where a diathermic oil is used to evaporate an organic working fluid to activate a turbine connected to an alternator. To maximise overall system efficiency, ORCs are normally composed of a pre-heater (diathermic oil/working fluid), an evaporator (diathermic oil/working fluid), a regenerator to recover the exhaust gas thermal energy, a condensator, a turbine and an asyncronous generator (low voltage) to produce electricity. The choice of an ORC system allows also the heat recovery for future possible installations near the plant location.

Travelling grate type boilers are more suitable than fixed grate type to a higher humidity content and mixed fuel such as the one under analysis. In these types of boilers, the combustion chamber is coupled with a post-combustion chamber to reduce the emissions in atmosphere and to guarantee full combustion of biomass and hence improve the overall efficiency. Ashes are collected by means of an *ad hoc* screw conveyor.

Overall efficiency is maximised also by means of a fumes/fresh air heat exchanger, which preheats the fresh air up to about 70 °C prior to enter the combustion chamber. Diathermic oil is heated up to 300 °C by means of a thermal power boiler. Table 2 shows main plant parameters.[1]

The scenario analyses have been conducted for three different size turbines based on the above mentioned technology. The primary energy and the consequent amount of feedstock needed are calculated based upon the number of operational hours and the feedstock LHVs. Wheat straw LHV is assumed equal to 14.0 MJ kg^{-1}, chipped wood LHV is assumed to be 13.3 MJ kg^{-1} [49].[2]

These values allow calculation of the amounts of chipped wood and wheat straw needed per each of the scenarios under analysis. Financial results depend on wood chips and wheat straw individual prices, which depend on market condition and feedstock characteristics (mainly the moisture content).

Table 5
Fuel mixes which maximize IRR for plants between 600 kW_{el} and 1000 kW_{el} running at least 6000 h per year, for different costs of wheat straw.

Cost of wheat straw [€ t^{-1}] (C_S)	Ideal % of chipped wood (% CW)
$C_S \leq 48.4$	0%
$48.4 < C_S < 63.5$	$\% CW = 0.053 \times C_S - 2.45$[a]
≥ 63.5	100%

[a] This equation is obtained as the linear fitting of the scatter plot of % of wood chips vs. price of straw which maximize IIR [%]. This linear fitting is showed in Fig. A4 (supplementary data).

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[1] The data and the statements regarding the boiler and the ORC turbine have been taken from manufacturers technical operational manuals available online.

[2] Chipped wood is assumed to reach the farm gate at 30% water content. The $LHV_{30\%}$ has been calculated from the values available at [49] (fuel at 50% moisture content) adding the energy required for evaporation of water reduction in kg (assuming 2.26 MJ kg^{-1} energy required for evaporation of water).

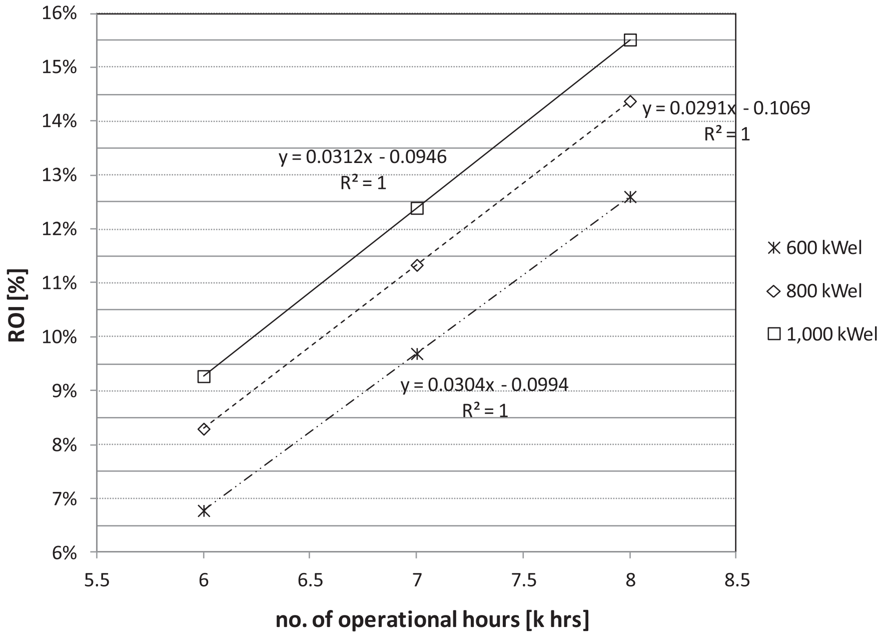

Fig. 14. ROI [%] for different plant sizes with respect to number of yearly operational hours.

The price for chipped wood considered in this study was taken from previous studies [49], assuming 30% moisture content and confronted with current European market data [50]. These data show substantially stable prices of chipped wood, hence, in this study we have assumed an average fixed value of 46,45 € t^{-1} (30% moisture content).

Price of wheat straw seem more critical to financial viability of the initiative as both previous studies [49] and current market[3] show a significant price variability linked to variability of wheat price and production volumes both within the same year and throughout the different years.

In this study we have assumed a price of wheat straw variable between 23.8 € t^{-1} and 95.2 € t^{-1} (15% moisture content). In summary, the scenario analyses are based on variation of the following figures:

- Plant size;
- Number of operational hours;
- Fuel mix composition;
- Price of wheat straw.

The schematics of the scenario analysis are explained in the diagram showed in Fig. 6. Data for evaluation of plants economics and financials are showed respectively on Table 3 and Table 4.

4. Results and discussion

Plants between 600 kW_{el} and 1000 kW_{el} power show a high IRR variability depending on plant size, number of operational running hours, feedstock composition and price of wheat straw. Values range between 0.06% and 52.17%. Financial viability (IRR > 15%) is ensured for any fuel mix and any wheat price, only if the number of operational running hours stays above 8000 h Figs. 7–12 show the IRR values obtained for plants of 600 kW_{el} and 1000 kW_{el} power, each for 6,000, 7000 and 8000 yearly operational running hours and different fuel mixes. Results are plotted with respect to wheat straw price (similar values obtained for 800 kW_{el} power plants are provided within the supplementary material).

The graphs show that financial returns significantly increase when price of straw is low and fuel mixes include low percentages of wood chips.

Plants of 600 kW_{el} running 6000 h per year are financially viable only if wheat straw price stays below 77 € t^{-1} and fuel mix contains at least 50% chipped wood. The percentage of chipped wood can be decreased to 25% if price of straw stays below 72 € t^{-1}. This fuel mix shows IRR up to 35.31% if price of straw is at its minimum value of 23.8 € t^{-1}. For this price, the IRR would rise up to 38.89% for a 100% wheat straw feedstock.

1000 kW_{el} power plants are financially viable for any fuel mix and any wheat price if number of yearly operational running hours stays above 7000 h. If number of yearly operational running hours drops to 6000 h, financial viability is ensured for any fuel mix, only if price of straw stays below 82 € t^{-1}.

Plants of 1000 kW_{el} running 8000 h per year boast high IRRs for any fuel mix and any wheat straw price. Managers of such plants would select fuel mix depending on their risk aversion. 100% wheat straw fuel may produce IRR as high as 90.61% if price of straw is at its lowest, but drops down to 24.00% if price of straw stays to its high level.

A risk averse manager could go for a 100% chipped wood fuel, and ensure 59.43% IRR irrespectively of wheat straw price. In general terms, and for all the scenario under analysis, when prices of wheat straw are above 63.5 € t^{-1}, the 100% chipped wood fuels always the most profitable. When prices of straw are below 48.4 € t^{-1}, the 100% straw feedstock shows the highest returns.

Fig. 13 shows IRRs of plants 1,000 kW_{el} power, running 8000 h per year, when price of wheat straw varies between 48.4 € t^{-1} and 63.5 € t^{-1} for the different fuel mixes. Optimal fuel mixes, with respect to maximization of IIR, are also shown for each of the wheat straw prices.

As mentioned above, the highest IRR of 66.8% is obtained when prices of straw are low and fuel is composed only of wheat straw. In this case, IRR decreases to 52.3% if price of straw increases to

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[3] http://www.cciaa.cremona.it; http://www.fc.camcom.it.

63.5 € t^{-1}. For 100% chipped wood feedstock financial return is 59.4% and risk connected to straw price variation is eliminated.

If prices of straw stays at its average value of 59.5 € t^{-1}, the maximum IRR of 60.3% is obtained for fuel mix of 68.2% wood chips. When price of straw is around 55 € t^{-1}, returns show the smallest dependence on fuel mix as IRR may vary between 59.4% and 62.3% whichever the mix.

As it can be deducted by Figs. 7–12, the latest conclusions may be drawn also for plants sizes of 600 kW_{el} (refer to supplementary material for plants of 800 kW_{el}) and annual operational running above 6000 h.

Table 5 shows the fuel mixes which maximize IRR for plants between 600 kW_{el} and 1000 kW_{el} running at least 6000 h per year, for different costs of wheat straw.

Fig. 14 shows ROI for plants sizes 600 kW_{el}, 800 kW_{el} and 1000 kW_{el} for different running hours in the case of cost of wheat straw equal to 59.5 € t^{-1} and fuel mix composed of 50% wheat straw and 50% chipped wood. The graph shows similar sensitivity of plant size to number of operational hours. Per each of the plant size under analysis, there would be an average 3.0% gain on ROI per every 1000 extra running hours. In monetary terms, this would mean approximately € 137,000 extra yearly free cashflow.

Table 6 shows the main financial indicators for plant size 1000 kW_{el} and 8000 yearly operational running hours for price of straw equal to 59.5 € t^{-1} and fuel mix composed of 50% wheat straw and 50% chipped wood.

In addition to the above mentioned simulations, we have evaluated the sensitivity of IRR [%] with respect to biomass availability per each of the plant sizes under analysis. Different biomass availabilities are linked to different feedstock prices. We have assumed different prices depending on "low, medium or high" availability, as per the following Table 7.

The average cost of feedstock was calculated for 25% wheat straw and 75% wood chips fuel mix. This is in line with the choices of fuel mix for an average risk averse investor. The IRR [%] was then plotted with respect to average fuel price and plant size, assuming 8000 yearly operating hours (see Fig. 15).

Results show sufficient IRR [%] in any of the cases analysed. Sensitivities between 0.032 and 0.038 percentage points of IRR [%] are registered per each 100 kW increase in plant size. The highest sensitivity is calculated for the lowest feedstock price, i.e. maximum feedstock availability.

4.1. Life cycle cost analysis

A biomass plant represents a long term investment, thus performing life cycle cost analysis (LCCA) is very important in order to fully evaluate all the economic implications across the useful life of the project.

Table 6
Main financial indicators for plant size 1000 kWel and 8000 yearly operational running hours.

Financials resume	Values
Total investment	€ 4,378,749
Debt	€ 3,502,999
Equity	€ 875,750
Average annual revenue	€ 1,904,000
Average annual free cashflow	€ 679,407
NPV	€ 4,461,883
ROS	35.68%
ROI	15.52%
ROE	77.58%
BCR	101.90%
Equity PbT [yrs]	1.88
Equity IRR	59.86%

Table 7
Different biomass availabilities for different feedstock prices.

Availability	Wheat straw [€]	Wood chips [€]	Weighted average [€]
Min	95.2	50.0	61.30
Med	59.5	46.45	49.71
Max	23.8	42.90	38.13

The LCC has been calculated based on Equation (1) [52]:

$$\mathrm{LCC} = \mathrm{Capital} + \mathrm{Replacement\ cost} + \mathrm{Maintenance\ cost} + \mathrm{Energy\ cost} - \mathrm{Salvage} \tag{1}$$

where, Capital is the present value of investment, Replacement cost is the amount of money at present value that may occur during the years, Maintenance and Energy costs are annual values and converted to present date. Finally, Salvage is the amount of money, at present value, which could be recovered for dismissal of the plant. All values are actualized to present date by an interest rate equal to the WACC.

For the case under analysis, values are shown below:

- *Investment cost*: € 4,378,749;
- *Replacement costs*: according to manufacturer's data [53,54], are assumed to be null if maintenance program is fulfilled for the 15 years life span of the equipment;
- *Maintenance costs*: boiler and cogenerator sum up to € 496,449;
- *Energy costs*: € 1,232,564;
- *Salvage cost*: € 138,036. The calculation is based on manufacturer's data [52,53]: after 15 years equipment life can be calculated as 10% of original value. A single cashflow of € 437,874, occurring in year number 15, has been actualized as described above.

According to Equation (1), the LCC of the plant is then equal to:

$$\mathrm{LCC} = €\,4,378,749 + €\,496,449 + €\,1,232,564 - €\,138,036 = €\,5,969,727 \tag{2}$$

The Annual Life Cycle Cost can be calculated as the annual flow which, in 15 years, at present date would total the LCC. The value at

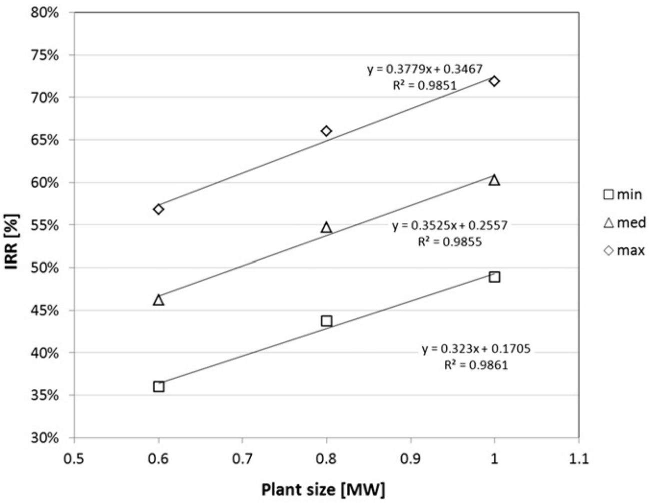

Fig. 15. IRR [%] with respect to average fuel price and plant size.

8% interest rate is € 697,440. The total LCC per gross MWh produced is then € 152.23.

5. Conclusions

This work highlighted the potential financial returns of a 600 kW_{el} ÷ 1000 kW_{el} ORC biomass fuelled power plant coupled with a travelling grate boiler, fed with different mixes of chipped wood and wheat straw collected within a radius of 20 km from the assumed plant location, in an area of inland Sicily.

GIS was used to pre-assess investment feasibility with respect to local biomass availability and distribution. A number of scenario analyses based on plant size and number of operational running hours, allowed evaluation of financial returns connected to fuel mix and price of feedstock. In particular, we have highlighted how plant returns are significantly influenced by high variability of price of wheat straw.

For what concern this study, we may conclude that biomass-fed power plants sized between 600 kW_{el} and 1000 kW_{el} are financially feasible for any locally based wood chips-wheat straw fuel mix and any feedstock price, only if 8000 yearly operational running hours can be ensured. In any other case, maximization of plant return (IRR) requires selection of the appropriate fuel mix for each price of wheat straw. Fuel mixes which maximize plant returns for different price of wheat straw were also calculated alongside with plant IRR per each of the cases.

Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.energy.2012.07.036.

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